Atom-number amplification in a magneto-optical trap via stimulated light forces

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We decelerated an atomic beam of ^{87}Rb using a stimulated-emission slowing technique that employs a bichromatic standing light wave of high intensity, and increased the atom number in a magneto-optical trap (MOT) of low capture velocity by up to a factor of 14, and the load rate into the MOT by a factor of 20. We performed the slowing over distances under 1.5 cm with 5.2 mW of total power in the bichromatic beams. The average stimulated force was 2.2 times the maximum spontaneous emission force, and could be made even stronger in a smaller apparatus.

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Laser cooling and trapping [1] have led to improved metrology with atoms. The most sensitive frequency measurements [2,3] and inertial sensing applications [4,5] using cold atoms are performed in laboratory settings with extensive experimental hardware. The ability to create a cold-atom sample in a compact vacuum package would enable the development of portable atomic devices with improved sensitivity, such as clocks and inertial sensors, potentially as fully integrated instruments.

It is well known that the number of atoms in a magneto-optical trap (MOT) or molasses loaded from a thermal vapor scales strongly with the size of the trapping region [6–9]. The steady-state number of atoms N_{SS} can be written in terms of the capture velocity v_{cap} as $N_{SS} = (V^{2/3}/\sqrt{6}\sigma)(v_{\text{cap}}/\overline{v})^4$ [6]. Here, V is the trap volume defined by the intersecting MOT beams, $\sigma = 2 \times 10^{-13}$ cm^2 is the cross section for atom loss from background collisions, and $\overline{v}$ is the mean thermal speed.

The simplest models [6] assume a MOT slowing force that is independent of atom velocity. In this case, basic kinematics show that with a photon scatter rate R_{sc} and photon momentum $\hbar k$, $v_{\text{cap}} = (2dR_{\text{sc}}\hbar k/m)^{1/2}$, and hence $N_{SS} \propto d^4$. More sophisticated modeling shows that $N_{SS} \propto d^{3.6}$ [8], which is consistent with experimental measurements for trapping volumes greater than 1 cm^3 [7,8]. Recent experimental results on millimeter-scale pyramidal traps [10] show a stronger scaling, with $N_{SS} \propto d^6$. This scaling can be understood using a model in which the cooling force is proportional to the atom velocity, in which case $v_{\text{cap}} \propto d$ and the above equations result in $N_{SS} \propto d^6$. A slowing force proportional to atom velocity is consistent with the physics in a traditional molasses with a very small trapping region where $v_{\text{cap}} < \Gamma/k$ and Doppler effects can be neglected.

For an atomic-beam-loaded MOT, when the atomic-beam diameter is smaller than the laser-beam diameter and the loss rate is dominated by collisions from the atomic beam, $N_{SS} = (A_b/\sqrt{\pi}\sigma)(v_{\text{cap}}/\overline{v})^4$, where $A_b = \pi(d_b/2)^2$ is the cross-sectional area of the atomic beam. In beam-loaded MOTs, a counterpropagating laser beam can be used to slow fast atoms to below v_{cap} so that they can be captured in the MOT [11], thereby amplifying the number of trapped atoms. The changing Doppler shift as the atoms slow can be compensated for by using a spatially varying magnetic field [12] or by chirping the slowing laser frequency [13]. The length scale needed to slow thermal atoms is set by the mean atom velocity and the maximum spontaneous force $\hbar k\gamma/2$ to be approximately 1 m for alkali-metal atoms, where γ is the natural decay rate of the excited state.

Beam-deceleration methods based on stimulated emission provide a means of exceeding the spontaneous force limit by scattering photons at a rate much higher than $\gamma/2$ [14,15]. The bichromatic force employs stimulated emission in a standing light wave to exert a strong force over a large range of velocities [16,17]. Strong bichromatic forces have been used to slow a Cs beam [18], to slow and deflect Rb [19,20], and to collimate and slow metastable He [21]. Here, we use a bichromatically slowed atomic beam to load a MOT and demonstrate an increase in the loaded number of atoms over what is achievable by the maximum spontaneous force.

The bichromatic force can be explained intuitively with a π-pulse model [16]. An atom with velocity v interacts with two counterpropagating π-pulse trains composed of frequencies $w_0 \pm \Delta - \delta\omega$ and $w_0 \pm \Delta + \delta\omega$ [Fig. 1(a)]. The beat frequency is 2Δ, and the Rabi frequency is set to $\Omega_R = (\pi/4)\Delta$ such that the beats form π pulses. When $\Omega_R \gg \gamma$, the scattered photons can generate forces much higher than the spontaneous force limit. When the phase of the counterpropagating π pulses, ϕ, is set such that the beats are perfectly in or out of phase ($\phi = 0,\pi$), the stimulated force averages to zero. For other phase differences, the atom preferentially absorbs photons from one pulse train and emits photons into the other, generating a net force with the maximum occurring for $\phi = \pm\pi/2$. After each spontaneous emission event, the force direction can reverse, and the excitation-emission sequence that results in less time spent in the excited state produces a stronger force and determines the force direction.

When the π-pulse condition is met and ϕ is optimized, the ideal bichromatic force magnitude is $\hbar k\Delta/\pi$, which is a factor of $\xi = 2\Delta/\pi\gamma$ stronger than the maximum spontaneous force. The force profile is broad, addressing velocities over a range of $\approx\Delta/k$ centered at $\delta\omega/k$. Careful measurements of the bichromatic force suggest that the actual magnitude reaches about 2/3 of the above ideal value, but the width of the force profile is accurately estimated [20].

For atoms subject to a force of $\xi\hbar k\gamma/2$, the maximum atomic velocity that can be slowed to v_{cap} over an interaction length L is $v_{\max} = (v_{\text{cap}}^2 + \xi\hbar k\gamma L/m)^{1/2}$. By slowing an atomic beam before loading it into a MOT, the

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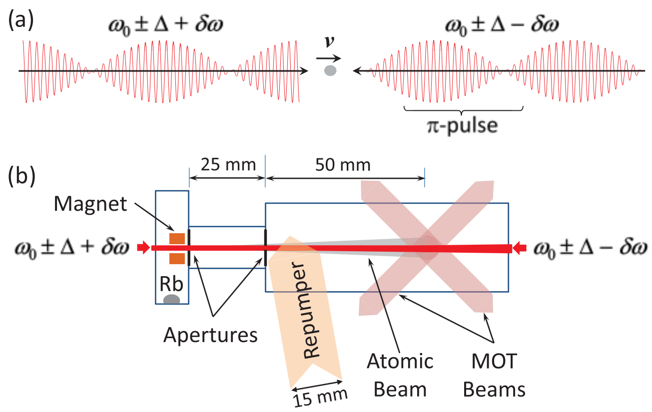

FIG. 1. (Color online) (a) The π-pulse picture of bichromatic slowing. For deceleration, the phase of the bichromatic beats is set such that the atom absorbs photons from the $\omega_0 \pm \Delta - \delta\omega$ beam and emits them into the $\omega_0 \pm \Delta + \delta\omega$ beam. (b) Schematic diagram of our experimental apparatus (see text).

captured atom number is larger than the MOT number loaded from a thermal beam by the enhancement factor $E = [1 + \xi\hbar k\gamma L/(mv_{\mathrm{cap}}^2)]^2 = (1 + \xi L/d_{\mathrm{sat}})^2$, where d_{sat} is the beam diameter for a MOT formed from fully saturated laser beams with capture velocity v_{cap}. For spontaneous slowing, $\xi = 1$, whereas for stimulated slowing, $\xi > 1$.

The maximum slowing length in our apparatus is set by the system geometry to 15 mm. The actual slowing length is reduced from this maximum value by the duty cycle D, with which we apply the slowing light, defined as the fraction of time that the bichromatic field is on. Varying D allows us to measure the enhancement versus "effective slowing length," LD, to test how the bichromatic force scales with miniaturization. The slowing length is limited by the partial spatial overlap between the atomic beam and the bichromatic light due to imperfect mode matching, which shortens the slowing length by an additional factor η. These effects change the enhancement to $E = (1 + \eta\xi LD/d_{\mathrm{sat}})^2$, which holds when LD is shorter than the stopping length, $L_s = mv_{\mathrm{max}}^2/(\xi\hbar k\gamma)$. Technical restrictions in our experiment allow a maximum of $\Delta = 20\gamma$, which limits ξ to a maximum of $\xi = \frac{2}{3}\frac{2\Delta}{\pi\gamma} = 8.5$, and gives a minimum stopping length of $L_s = 5.2$ mm. We use these approximate scaling arguments for interpreting the experimental data presented below.

Our apparatus, shown in Fig. 1(b), was designed to test how bichromatic slowing scales with miniaturization in terms of the laser power needed to apply a strong force and the interaction length necessary to slow atoms to the low capture velocities of compact MOTs. A Rb atomic beam flows from a 150 °C oven to a second vacuum chamber through a collimator consisting of two 0.5 mm apertures separated by 25 mm. A permanent magnet before the first aperture detunes the atoms far from resonance in the source chamber, reducing absorption of the bichromatic beams within the dense Rb vapor [18]. The distance from the second aperture to the MOT is 5 cm. The atomic beam expands to a diameter $(1/e^2)$ of 2.2 mm at the MOT region.

The atomic beam is loaded into a MOT of 6.6-mm $1/e^2$ beam diameter. We typically use a MOT beam power of 100 μW, which corresponds to $v_{\mathrm{cap}} \simeq 5.5$ m/s [8]. This low MOT beam power simulates a MOT with $d_{\mathrm{sat}} = 0.5$ mm, while ensuring that the majority of the slowed atoms in the diverging atomic beam intersect the trap and simplifying alignment in our large experimental apparatus.

The circularly polarized bichromatic laser beams are focused through the chamber with 1 m focal-length lenses, producing a focused beam diameter of 0.32 mm $(1/e^2)$ between the apertures. Each bichromatic beam carries 1.3 mW of power, giving a total of 5.2 mW. The circular polarization of the bichromatic light ensures efficient slowing since the $F = 2 \rightarrow F' = 3$ cycling transition provides a nearly ideal two-level system. When Zeeman shifts from the MOT and atom source magnets are significant in the cooling region, there can also be an optimum handedness for the circularly polarized slowing light. With our typical experimental parameters, we estimate that we apply a maximum force of $4.2\hbar k\gamma$ and address atoms with velocities up to 120 m/s.

The four frequencies that form the bichromatic standing wave are generated with three acousto-optic modulators (AOMs). Our laser configuration allows for independent control of the Δ and $\delta\omega$ frequencies, enabling distinct optimization of the width and center velocity of the bichromatic force profile.

The maximum slowing length in the apparatus is set by the overlap between the bichromatic light and a hyperfine repumper laser tuned to the $F = 1 \rightarrow F' = 2$ D1 transition, preventing buildup of atoms in the $F = 1$ ground state. For our MOT loading experiments, a 15-mm-long stripe of repumper light enters the apparatus just below the collimator, oriented transversely with respect to the atomic beam and the bichromatic light.

To tune the slowing length between 0 and 15 mm, we vary the duty cycle of the bichromatic light by pulsing the beams on microsecond time scales. Estimating the slowing length from the duty cycle and repumper interaction region overestimates the slowing length at lower duty cycles, as the radial expansion of the atomic beam exceeds the divergence of the slowing light. Further from the collimator, fewer atoms overlap the slowing beams such that after 15 mm, only 16% of the atom flux remains within the bichromatic field.

The MOT atom number is measured via fluorescence on a photomultiplier tube [22]. The MOT has a typical loading time constant of 2 s. With the bichromatic light off, we typically load about 7000 atoms with 100 μW MOT beam power, and about 100 000 atoms for 900 μW MOT beams. These numbers agree with the expected values of N_{SS} calculated from the simple expressions given above to within a factor of two.

An example of an approximate force profile applied in our experiment is shown in Fig. 2. Here, the width is Δ/k and the center is $\delta\omega/k$. The force magnitude is set to the ideal value of $\hbar k\Delta/\pi$ scaled by the factor of 2/3 measured previously [20]. Also shown are longitudinal velocity distributions that have been modified by the application of bichromatic forces with ϕ set to $\pm\pi/2$. The altered velocity distribution in the regions near the active force profile demonstrates the effects of the bichromatic field. Atoms are slowed when the phase is set to $+\pi/2$ and are accelerated when the phase is set to $-\pi/2$. For these measurements, the repumper and probe laser were overlapped with the cooling light and applied longitudinally

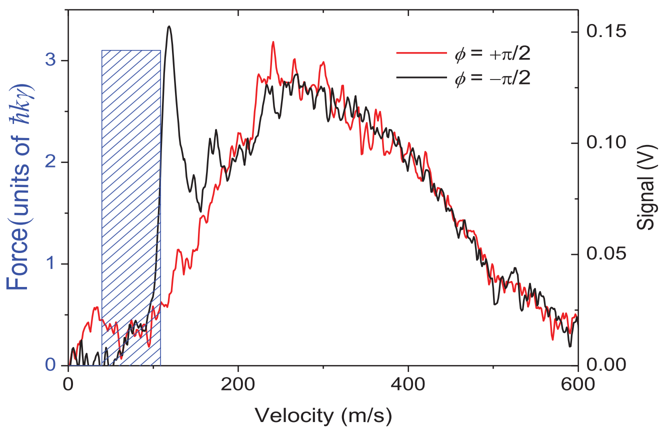

FIG. 2. (Color online) Measured atomic-beam-velocity distributions with ϕ set to $+\pi/2$ for deceleration and $-\pi/2$ for acceleration. The approximate range of the stimulated force profile is shown as the hatched area for bichromatic parameters of $\Delta = 14.6\gamma$ and $\delta\omega/k = 74$ m/s. The bichromatic light was applied with a duty cycle of 0.5 (see text).

such that the bichromatic force was active between the collimating apertures. Because the bichromatic force only affects the longitudinal atom velocity, the divergence angle for the addressed atoms changes by a factor of $\sim v_i/v_f$, where v_i and v_f are the initial and final longitudinal velocities, respectively. Thus, the divergence angle for accelerated atoms decreases, while it increases for decelerated atoms, altering the sample of probed atoms. Additionally, increased atomic-beam divergence within the collimator causes some atoms to be skimmed by the second aperture. A combination of these two effects causes the imbalance in the peak heights in Fig. 2. We ultimately oriented the repumper light transversely to the atomic beam and applied it after the collimator to minimize cold-atom loss.

Most of our MOT loading experiments were performed with $\Delta = 20\gamma$ and $\delta\omega = 15.7\gamma$, which centers the force profile on a velocity of 74 m/s. The force profile was 40% stronger and broader than the one shown in Fig. 2. The optical path lengths of the slowing light were tuned to establish a $+\pi/2$ phase difference, and the average Rabi frequency was set to 24.5γ, corresponding to an average intensity of $1200 I_{\rm sat}$. For a performance comparison, we also decelerated our atomic beam by use of spontaneous emission. In these experiments, we used a single counterpropagating laser beam at a detuning of -17.5γ with a saturation parameter of 1200, giving a power-broadened linewidth of 35γ. The beam had the same geometry as the bichromatic beams.

In Fig. 3, we plot the MOT atom number and rate enhancements versus duty cycle and effective slowing length for bichromatic and spontaneous force slowing. Compared to loading from a thermal beam, we observe a maximum number enhancement of 14 for the bichromatic force method compared to 10 for the spontaneous force method, while also measuring loading rate enhancements of up to 20 for bichromatic forces and 13 for spontaneous forces. From the basic equations for N_{SS}, we would expect the load rate and number enhancements to be the same. They could differ because either our fluorescence detection method is saturating

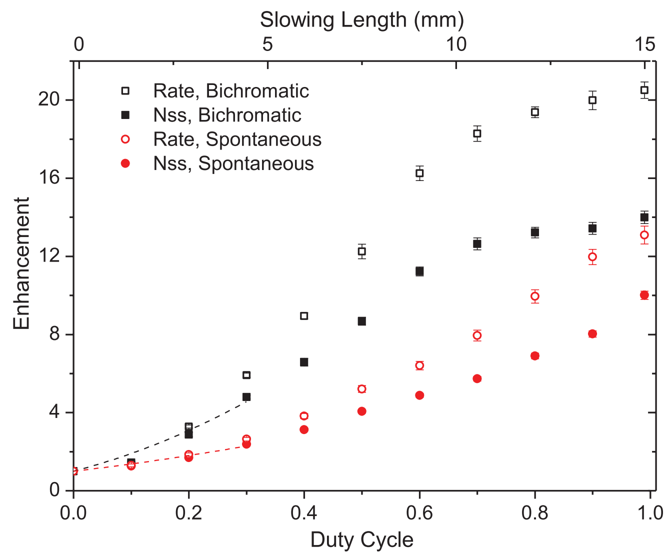

FIG. 3. (Color online) Atom-number (solid symbols) and rate (open symbols) enhancement vs duty cycle and effective slowing length for bichromatic slowing with $\Delta = 20\gamma$ and optimized spontaneous slowing. Also, shown are one-parameter fits of the number-enhancement data to the function $E = (1 + CD)^2$ at low duty cycles, where $C = \xi\eta L/d_{\rm sat}$. Here, an enhancement of 14 corresponds to $\sim$100 000 atoms.

and artificially suppressing our atom-number measurement, or because the MOT atom density is saturating in our compact MOTs from an additional loss mechanism. From absorption measurements, we estimate our peak MOT density to be 1×10^{10} cm^{-3}, which is smaller than the saturated density of 2×10^{11} cm^{-3} that has been observed in larger MOTs [23]. Some loss may arise from the bichromatic light intersecting the MOT beams.

The spontaneous signal grows steadily with effective slowing length, but the enhancement from bichromatic slowing begins to saturate for longer interaction lengths. The slowing length where the bichromatic signal begins to depart from a quadratic dependence and saturate roughly agrees with the stopping distance of 5.2 mm expected for our optimized bichromatic force profile. After 5.2 mm, all of the atoms that are still within the slowing beams that had initial velocities within the force profile are already maximally slowed and no longer interact with the bichromatic field. The spontaneous force does not saturate for our short slowing lengths since it is much weaker and addresses a large, power-broadened velocity class (164 m/s, FWHM). For our bichromatic parameters, the full advantage of the stimulated slowing method is therefore realized only for slowing lengths under 1 cm.

To determine the dependence of the number enhancement on beam power, we varied the MOT beam power from 100 to 900 μW. The enhancements are typically twice as large for the lower powers. We also performed measurements at a lower value of $\Delta = 16.8\gamma$, which results in a 20% weaker force with a 20% narrower force profile. The maximum enhancements with the lower Δ were about half as large as the enhancements observed with $\Delta = 20\gamma$.

In terms of enhancement, bichromatic slowing is more effective than spontaneous slowing in our system, but an analysis of the data in Fig. 3 suggests that the results could be improved. With $d_{\text{sat}} = 0.5$ mm and $L = 15$ mm, the fit to the spontaneous data gives $\eta = 0.057(4)$. The fit to the bichromatic data gives $\xi = 2.2(2)$, which is $\sim$4 times lower than the expected force. This discrepancy most likely arises from the inhomogeneous intensity profile of the Gaussian beams, which results in deviations from the ideal π-pulse condition for optimized bichromatic forces. The π-pulse condition is only satisfied along a cylindrical shell of the beams, and, in fact, we estimate that the spontaneous force profile integrated over velocity is larger than the integrated bichromatic force profile for radii larger than $\sim 0.6 w_0$, where w_0 is the Gaussian waist diameter ($1/e^2$).

The performance of bichromatic slowing could be improved with a smaller, more optimal apparatus. About half of the atoms in our atomic beam never see the slowing light at all since the collimator aperture diameter (0.5 mm) is larger than the slowing beam diameter (0.32 mm, $1/e^2$). Additionally, as mentioned above, the atomic beam diverges as it travels toward the MOT, such that only about 16% of the atoms overlap the bichromatic light at the end of the interaction region. When the slowing field is on, the radial spread is even worse as a function of distance. The limitations from transverse spreading could be significantly diminished with an improved experimental geometry based on a shortened overall apparatus length. This would facilitate improved mode matching of the atomic beam to the bichromatic light, which would increase the number of atoms addressed and would enable a more optimized intensity distribution. Also, the enhancements we observe in our large system are very sensitive to the precise alignment of the bichromatic beams. We have observed brief MOT number enhancements of up to 20 and rate enhancements of up to 40. Consistently achieving optimal beam alignment would also be easier in a smaller system.

By slowing a thermal atomic beam with the bichromatic force, we have demonstrated MOT number enhancements of up to 12.5 and load-rate enhancements of 18 for effective slowing lengths under 1 cm. The number and rate enhancements are $\sim$2.5 times larger than the enhancement observed for spontaneous force slowing. Bichromatic slowing could potentially be important for highly miniaturized instruments based on cold atoms. It is also conceivable that a three-dimensional (3D) bichromatically slowed optical molasses could be created, though there is an intrinsic trade-off between the required power and trap volume in such a system. Future experiments will explore the use of the bichromatic force to produce atom numbers consistent with large-scale systems in microfabricated packages.

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[1] H. Metcalf and P. van der Straten, *Laser Cooling and Trapping* (Springer, New York, 1999).
[2] M. A. Kasevich, E. Riis, S. Chu, and R. G. DeVoe, Phys. Rev. Lett. **63**, 612 (1989).
[3] A. Clairon, C. Salomon, S. Guellati, and W. D. Phillips, Europhys. Lett. **16**, 165 (1991).
[4] H. Müller, S. W. Chiow, S. Herrmann, S. Chu, and K. Y. Chung, Phys. Rev. Lett. **100**, 031101 (2008).
[5] D. S. Durfee, Y. K. Shaham, and M. A. Kasevich, Phys. Rev. Lett. **97**, 240801 (2006).
[6] C. Monroe, W. Swann, H. Robinson, and C. Wieman, Phys. Rev. Lett. **65**, 1571 (1990).
[7] K. E. Gibble, S. Kasapi, and S. Chu, Opt. Lett. **17**, 526 (1992).
[8] K. Lindquist, M. Stephens, and C. Wieman, Phys. Rev. A **46**, 4082 (1992).
[9] A. M. Steane, A. M. Steane, M. Chowdhury, and C. J. Foot, J. Opt. Soc. Am. B **9**, 2142 (1992).
[10] S. Pollock, J. P. Cotter, A. Laliotis, F. Ramirez-Martinez, and E. A. Hinds, New J. Phys. **13**, 043029 (2011).
[11] S. Chu, L. Hollberg, J. E. Bjorkholm, A. Cable, and A. Ashkin, Phys. Rev. Lett. **55**, 48 (1985).
[12] W. D. Phillips and H. Metcalf, Phys. Rev. Lett. **48**, 596 (1982).
[13] W. Ertmer, R. Blatt, J. L. Hall, and M. Zhu, Phys. Rev. Lett. **54**, 996 (1985).
[14] A. Aspect, J. Dalibard, A. Heidmann, C. Salomon, and C. Cohen-Tannoudji, Phys. Rev. Lett. **57**, 1688 (1986).
[15] M. Prentiss and A. Cable, Phys. Rev. Lett. **62**, 1354 (1989).
[16] V. S. Voitsekhovich, M. V. Danileiko, A. M. Negriiko, V. I. Romanenko, and L. P. Yatsenko, Pis'ma Zh. Eksp. Teor. Fiz. **49**, 138 (1989) [JETP Lett. **49**, 161 (1989)].
[17] A. P. Kanzanstev and I. V. Krasnov, J. Opt. Soc. Am. B **6**, 2140 (1989).
[18] J. Söding, R. Grimm, Yu. B. Ovchinnikov, Ph. Bouyer, and Ch. Salomon, Phys. Rev. Lett. **78**, 1420 (1997).
[19] M. R. Williams, F. Chi, M. T. Cashen, and H. Metcalf, Phys. Rev. A **60**, R1763 (1999).
[20] M. R. Williams, F. Chi, M. T. Cashen, and H. Metcalf, Phys. Rev. A **61**, 023408 (2000).
[21] M. Partlow, X. Miao, J. Bochmann, M. Cashen, and H. Metcalf, Phys. Rev. Lett. **93**, 213004 (2004).
[22] D. A. Steck (unpublished), [http://steck.us/alkalidata].
[23] C. G. Townsend, N. H. Edwards, C. J. Cooper, K. P. Zetie, C. J. Foot, A. M. Steane, P. Szriftgiser, H. Perrin, and J. Dalibard, Phys. Rev. A **52**, 1423 (1995).